DEFINING OPTIMUM PHOTOMECHANICAL COLOUR REPRODUCTION

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Abstract: Whilst a large proportion of colour reproduction is very pleasing there is no objective measure of what constitutes a good reproduction. In general a colorimetric match does not prove satisfactory and the principal reasons for this are well known. What is required is a model which defines colour appearance. Recently two comprehensive models have been proposed by Hunt (1987) and Nayatani (1987). These are in the process of being evaluated for our application and this paper will provide a status report of this work and discuss how well it applies to Graphic Arts.

Introduction

Manufacturers of colour reproduction equipment have long had an ambition to simplify the process. It has always been seen as a desirable objective to minimise the subjective interpretation introduced by operators. Whilst various attempts have been made over the years to achieve this all have failed to eliminate it to any significant degree. Many people conclude from this that an objective interpretation of colour reproduction is impossible. Whilst I accept that there is some limited truth in this I cannot believe it as a general rule. My ambition in this paper is to briefly outline the reasons for limited success in the past and to report on the progress of some work being undertaken to change this situation.

Objectives in Graphic Arts Colour Reproduction

When presented with an original for reproduction only three alternative objectives seem feasible. Either a facsimile or a pleasing reproduction must be required and in

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addition <u>specific</u> editorial changes may be requested together with either of these. We know from many studies, as well as the evidence of our own eyes, that a facsimile reproduction can rarely be achieved. For example, reproducing a colour transparency in a cold-set newspaper will rarely permit the full range of brightness and colourfulness to be matched. Clearly in such circumstances we must conclude that a pleasing reproduction is required and the question to be answered is can we quantify it?

In practice I believe that the pleasing reproduction category needs further sub-division according to whether the original is deemed pleasing itself. Clearly if it is we could expect to define the optimum reproduction more reasonably than when it is not. This can be described as facsimile reproduction <u>taking account of process limitations</u>. In this paper I will concentrate on this situation. In another recent paper (Johnson, 1989) I have considered the situation where the original is not pleasing and indicated areas for further research in relation to this but do not propose to dwell on it here.

This limitation may seem exceptionally restrictive since many originals presented for reproduction do not seem to be pleasing. However, much of that decision depends upon how they are viewed and this is key to my thesis. I contend that the problems encountered in many previous attempts to quantify colour reproduction have come directly from the measurement limitations. The work described in section 4.0 of this paper is being undertaken to overcome this.

Various attempts have been made in the past to produce a colour scanner which will measure the colour of an original and reproduce it on paper. The first of these to use psychometric measures was described in various papers by Korman and Yule in the early 1970's (see, for example, Korman and Yule, 1971), and more recently the Eikonix corporation has produced a scanner utilising this principle (Masia, 1984).

Neither of these can claim to have been outstanding commercial successes to date and it is interesting to compare this with the success of a range of colour scanners from various manufacturers (e.g. Crosfield, Hell and Dainippon Screen) which really make no pretence to be colorimetric; they rely for their colour accuracy on defining the dye absorptions of the photographic materials being scanned and using approximations to conventional colour correction theory to reproduce them.

Obviously the reason for success, or otherwise, of a colour scanner does not lie solely in its colorimetry but it is nevertheless, worth speculating as to whether or not such an approach has been partly responsible for this lack of commercial success and whether it can ever be successful. I have few doubts about this; I believe it to be the only logical direction if we are to move towards a fully objective colour reproduction system. However that will only be achieved when we have resolved the current limitations of colorimetry in this respect; in particular the fact that colorimetry does not measure appearance. This limitation is one that does not seem clear to many people who propound it's widespread use in graphic reproduction and yet it is fundamental if we are to utilise the undoubted advantages colorimetry can bring. Until that time the semi-empirical approach of "conventional" colour scaners seems likely to be dominant.

This discussion is hardly novel; it has been aired on numerous occasions previously. The whole subject and relevant literature was reviewed in some depth by Johnson (1982) and summarised in a previous TAGA paper, Johnson (1985). In that latter presentation it was suggested that we could only expect to complete the transition to colorimetric scanning when the proper appearance measurements could be established, particularly for D5000 illuminant. It is my contention that only then will the advantages outweigh the disadvantages. Since that time Crosfield have been supporting research work to establish such parameters and whilst not yet complete we now have a much better understanding of the relationships. In section 4.0. a summary of the work to date is presented. This work will be extended further in the future and described at appropriate conferences. Obviously there will be parallel work undertaken to confirm whether such systems really offer the advantages anticipated when compared to "conventional" scanning methods.

It should be noted that I am not denying the usefulness of colorimetry, nothing could be further from my mind. Properly used, as for colour specification, it is an invaluable tool. However, if we attempt to use it for areas in which it is not so relevant, at least without transforming the data, we are only going to retard it's use generally.

Measurement of Appearance

Colorimetry is a deceptive subject. At first sight it appears very simple. It has been demonstrated that all observers who do not suffer from colour "blindness" require very similar amounts of three stimuli (such as cyan, magenta and yellow printing inks) to match any colour. From that "simple" demonstration a set of stimuli were standardised (called, imaginatively, XYZ) and an international measurement system established in 1931. Since the system is based on colour matching observations it tells us that if two colours have the same XYZ tristimulus values they must look the same. From this basis a number of parameters were established, such as dominant wavelength and purity which had a crude correlation with the perceptual sensations of hue and saturation.

Unfortunately it soon became realised that the non-uniformity of the colour space defined by XYZ meant that the system was not useful for defining colour differences (or tolerances) and emphasised the crudeness of the correlation between such parameters as hue and dominant wavelength. Thus in 1960/63 a "uniform" transformation of XYZ was introduced. This was superceded in 1976 by two other transformations now known as CIELUV and CIELAB. Such a space has the advantages that the perceptual correlates such as hue angle are more uniformly distributed than the equivalent parameters such as dominant wavelength in the XYZ space and hence that tolerances are now more meaningful.

Even this is not completely satisfactory, however. Such a space (even were it perfectly uniform) can only be strictly correct for one condition of viewing. Thus as visual adaptation changes or simultaneous contrast effects are introduced the uniformity of the space must deteriorate. We are fortunate that colour constancy prevails which means that many changes are small; nevertheless they exist. For many practical purposes such problems are not relevant; the changes due to adaptation are small compared to the non-uniformity of the spaces themselves. Nevertheless it is clear that if we are to define appearance such definitions are clearly limited and need further development.

To differentiate these terms we call the former psychophysical (since they simply define that two physical stimuli match) and the latter psychometric (since they are used to define the difference between two stimuli). What we require, however, is a psychoquantitative measure which allows us to determine the change of appearance of a stimulus as the condition of viewing changes.

At present no internationally agreed psychoquantitative definitions exist although many have been proposed. Probably the best known is that of Bartleson and Breneman, 1967 (a) and so I have used it in the following example to attempt to clarify the difference between these terms.

Psychophysical lightness (luminance factor) = $L/L(n)$
Psychometric lightness = $116\,(L/L(n))^{1/3}-17$
Psychoquantitative lightness = $\text{antilog}\,[(a+b\log L - [c\exp(d\log L)]) - (a+b\log L(n) - [c\exp(d\log L(n))])]$

Note: in the above L is luminance, L(n) is luminance of the white and a,b,c and d are parametric constants which change with viewing conditions. The psychoquantitative formula can be simplified but I have left it in this form for those who are familiar with it as a measure of brightness. To get a feel for the differences engendered by these formulae consider the 20% luminance factor. This produces a 50% psychometric lightness when transformed to a uniform scale. Depending upon viewing conditions the psychoquantitative equivalent will vary from approximately 35% to 50% using the above formula.

It can be argued that the psychometric measures make a perfectly valid set of measures for graphic reproduction since we are essentially trying to obtain a colour match to the original. The appearance is therefore not relevant. However, I dispute that for two reasons. Firstly many photographic originals are produced to look correct when properly viewed and so the definition of the colour should take account of the viewing condition in order to produce the match. This has been discussed extensively in an earlier paper, Johnson (1977). However, equally importantly, even where we standardise the viewing condition the difference of the visual field in viewing monitors, transparencies and prints undoubtedly means that conventional colorimetry will fail to predict a match due to factors such as flare. Though such factors can be overcome by using telecolorimetry a "tele-scanner" seems somewhat ambitious. Thus in the same way that psychometric measures proved necessary as a replacement for psychophysical measures in setting tolerances for matching I maintain that psychoquantitative measures will prove necessary for setting tolerances and defining gamut compression techniques in colour reproduction.

During recent years a colour appearance model has been developed by Hunt culminating in a paper in 1987. It is this model, together with one from Nayatani et al (1987) which we have been attempting to evaluate. The work has been funded by Crosfield Electronics with UK government assistance and carried out at Loughborough University in England. Initially we have taken the simple approach of using appearance modelling to quantify the colour match between colour monitors for soft proofing and reflecting samples such as those used for proofing. Further work is still required to extend the model where significant gloss differences from our reflecting samples occur and for transmitting samples seen in transparency viewing conditions. Nevertheless, the results obtained so far, together with our existing knowledge from the various papers described earlier are leading us to a far greater understanding of the matching problems. Some of the results to date were presented in an earlier paper by Luo et al (1989) but in the next section we describe those of most immediate significance to the above discussions.

As was stated in an earlier TAGA paper, Johnson (1985), Crosfield already make use of psychoquantitative lightness scaling using the Bartleson and Breneman equation and we find it very successful. Nevertheless it does have limitations in the way it is used. Because lightness and chromaticity are not directly separable in a "conventional" scanner the lightness is equated to grey component which is strictly only correct for monochrome originals. Since the "chromatic component" is then defined by residual densities (or dot areas) which also have a lightness component for real inks the colour correction parameters of the scanner must be set empirically to achieve three objectives: a) correct for lightness errors in chromatic areas (and this will alter as tone is changed); b) correct for unwanted ink absorptions and c) correct for metameric effects of the originals.

It must be said that in practice the situation is not as uncontrolled as the last paragraph would make it sound. Rules can be set to define the correction for lightness error, unwanted ink absorptions are easily measured and the range of originals encountered is sufficiently limited to require only a small number of data sets be established. By combining the rules for lightness error correction with predictions made from measuring inks with the small set of original requirements the empiricism can be substantially eliminated. Hence my earlier use of the term semi-empirical methods.

Nevertheless it must be clear that a colorimetric system which can properly separate lightness and chromaticity and use this as the basis for psychoquantitative data has potential advantages in overcoming these problems and defining optimum reproduction particularly where gamut compression is required. Whether these are sufficiently attractive to overcome the signal-to-noise ratio, crosstalk and computational complexity problems has yet to be proven. However, I firmly believe that until proper psychoquantitative models can be established such a system is very premature since most of the advantages cannot be properly enjoyed. It is for this reason that I suggest colorimetric systems have so far had limited success. I am nevertheless a strong enough believer to pursue the Research necessary to change this; hence our support for the work mentioned earlier.

Comparing Colour Appearance Models

As stated earlier two models for deriving psychoquantitative data have been proposed. Whilst we have been concentrating largely on that of Hunt (1987) we have also looked briefly at that of Nayatani (1987) and compared both to the CIELAB, CIELUV and CMC psychometric systems as far as possible. As stated earlier all the work was carried out at Loughborough University.

In total over 43,000 observations have been made by 10 observers in a variety of viewing conditions. Approximately 100 colours were assessed in each condition. The breakdown of this data is given in table 1. Clearly the D50 data is of most immediate relevance although we believe that for the other illuminants will prove valuable as the work is incorporated into our product design.

The technique used was to make magnitude estimations for the hue, colourfulness and lightness of each sample presented in a complex viewing field as shown in figure 1. The non-luminous samples consisted of a uniformly spaced selection from the OSA set viewed in a grey viewing booth and the luminous samples were those that matched the non-luminous samples on the colour monitor when both were measured with a telespectroradiometer. The distribution of samples is shown in figure 2. The experiment is described in more detail in the paper by Luo, the principal worker in this study, et al (1989). For the luminous samples both white and black borders of approximately 1.5 inches width were introduced to evaluate the effect of introducing such a border in soft proofing.

Hue scaling demonstrated a remarkable consistency under each adapting condition as the conditions of viewing were changed. In figure 3 two examples are given to demonstrate this. Figure 3 (a) shows the hue comparison for non-luminous samples as the intensity of illumination is changed and 3 (b) shows the same comparison for luminous samples as a white border is placed around the viewing field compared to when it is not present. The small deviation between hue 60 and 70 (around the yellow-green region) is, as yet, unexplained and represents the largest deviations seen for D50.

The importance of these results is clearly that, for a given chromatic adaptation condition, the hue of a sample does not change over a significant range of viewing conditions. Whilst such a result may be expected it is encouraging that it is confirmed.

Turning now to hue modelling figure 4 shows mean hue data obtained from this experiment plotted as a function of hue angle for CIELAB, CIELUV and CMC respectively and as a function of Hunt hue prediction for non-luminous samples. It should be noted that hue scales in the psychometric models are not designed to predict hue appearance and so figures 4 (a-c) are not strictly valid. This can be confirmed from these figures where the deviations are significant! The appearance models of both Hunt and Nayatani perform reasonably well in this respect although the Hunt model proved far superior with approximately half the coefficient of variation. (See table 2).

When we consider the colourfulness data two things quickly become apparent. The scatter of the data is much more significant than that for hue which indicates the difficulty found by observers in scaling colourfulness. Also the influence of viewing conditions on colourfulness, whilst significant, is not large. Two examples are given in figure 5 to demonstrate this. Figure 5 (a) shows the colourfulness change obtained when the non-luminous samples are viewed under both low and high level of illumination. As expected colourfulness increases with illumination level and is representative of the largest deviation seen. Figure 5 (b) shows the data obtained when comparing luminous and non-luminous colours seen at the same luminance level and surround colour. These show little significant difference.

Figure 6 shows the effect of varying the border around the luminous samples. Again it can be seen that any effect of the viewing condition is small.

Figure 7 shows a set of data for colourfulness similar to that for hue in figure 4. Our visual data is compared to CIELAB, CIELUV and CMC chroma and Hunt colourfulness values. The summary of the coefficient of variation is shown in figure 2 and this suggests that CMC is an equally good predictor of colourfulness as the Hunt model. However, this needs to be treated with caution, like much statistics. What this does not indicate is the slope of the data which is clearly not unity for CMC and which we would expect to change with viewing condition for psychometric data. An indication of this is given in figure 8.

Figures 8 (a) and (b) respectively show visual data as a function of CMC chroma and Hunt colourfulness for D50 illuminant. The slope of the CMC data is significantly different from unity although less scattered than the Hunt predictions. However for D65 (the natural choice for CMC) shown in figures 8 (c) and (d) this difference is far less pronounced. Clearly we require yet more statistical evaluation and this is part of our on-going work.

When we turn to lightness we are all aware, in general terms, of what to expect. The Bartleson-Breneman equation has been in existence for more than 20 years and has already been used for practical purposes in photography (Bartleson and Breneman, 1967 (b) and Hunt, 1988) and Graphic Arts (Johnson, 1977).

As expected the lightness differences are most dramatic. Of particular interest in the matching of monitors to proofs is the fact that a difference in lightness is established for these two conditions when samples have the same luminance. This is presumably due to flare. Examples of this are shown in figure 9 for both black and grey surrounds around the stimulus. The influence of the border around the viewing field is also marked, the same sample with black and white borders is shown in figure 10. This clearly demonstrates that conventional colour measurement will fail to predict the correct match between colour monitors and proofs for typical viewing conditions; psychoquantitative data is essential.

Figure 11 shows our lightness data plotted against the values predicted by CIELAB (and hence CIELUV), CMC, Nayatani's and Hunt's models. Clearly CMC is an exceptionally poor predictor of lightness and $L*$ is generally too light. Note that this is confirmed by the B&B model since as stated earlier the B&B equation predicts values of 35%-50% lightness (depending upon viewing conditions) when $L*$

is 50%. (This is, of course, at a luminance factor of 20%). What surprised us was the poor performance of the Hunt model in this situation since it seems to perform similarly to, if not worse than, L*. Whilst we have yet to prove it I suspect that the Bartleson-Breneman equation would have performed better in the model.

However, the Hunt model includes parametric constants which are designed to accommodate changes in viewing conditions and these were modified. (Nb was increased from 100 to 900 in the example shown). The resultant predictions are shown in figure 12.

Table 2 gives the coefficient of variation for the various models. It will be seen that the modified Hunt model (called ACAM) performs significantly better. Nevertheless, the caution mentioned earlier still needs to be borne in mind; individual peculiarities may be lost in these statistics.

The data provided in this paper is clearly only a very limited selection of the 43,000 observations. I have chosen them as examples of the work and to demonstrate some of the more interesting conclusions drawn to date. It clearly indicates that matching monitors to proofs cannot use conventional colorimetry and that appearance models do have significant benefits when the parametric constants are properly chosen. However, we are still in the process of analysing the data for its full implications to graphic arts and propose to publish a more detailed dissertation later this year. In this paper, and the earlier one published by Luo et al (1989), we have only concentrated on the D50 data. We also need to review the implications for chromatic adaptation when considering other sources. Perhaps most importantly, however, we still lack data for transmissive samples and plan to extend the work to include this in the future. We will then be in a position to develop a full psychoquantitative colour reproduction system.

Conclusions

The likely reasons for the failure of colorimetry in colour reproduction systems have been discussed and the lack of a proper psychoquantitative model cited as the likely reason. (This is <u>not</u> to be confused with colour specification, such as for inks, where colorimetry requires no justification; the case is indisputable!).

Preliminary results have been presented of the evaluation of both psychometric and psychoquantitative formulae. It has been shown that the latter can perform exceptionally well and can be used to demonstrate that matching colour monitors to proofs or prints cannot be achieved with the former. Further analysis of the data is still required to extend the conclusions to be sufficiently comprehensive for all viewing conditions and additional experimental work is still necessary, particularly for transmissive samples.

Acknowledgements

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Table 1

Phase	Illuminant	Luminance Level (cd/m²)	Surround	Mode	No. of Colours	No. of Obs.	No. of Estimation
1	D50	High (264.0)	White	Nonluminous	105	6	1890
2	D50	High (252.0)	Grey	Nonluminous	105	6	1890
3	D50	High (252.0)	Black	Nonluminous	105	6	1890
4	D50	Low (44.0)	White	Nonluminous	105	6	1890
5	D50	Low (42.0)	Grey	Nonluminous	105	6	1890
6	D50	Low (42.0)	Black	Nonluminous	105	6	1890
7	D50	Low (40.0)	White	Luminous	94	6	1692
8	D50	Low (44.5)	Grey	Luminous	100	6	1800
9	D50	Low (44.5)	Black	Luminous	100	6	1800
10	D50	Low (44.5)	Grey/White Border	Luminous	100	6	1800
11	D50	Low (44.5)	Grey/Black Border	Luminous	100	6	1800
12	D65	High (243.0)	Grey	Nonluminous	105	7	2205
13	D65	Low (40.5)	Grey	Nonluminous	105	7	2205
14	D65	Low (40.5)	Grey	Luminous	103	7	2163
15	D65	Low (40.5)	Grey/White Border	Luminous	103	7	2163
16	WF	High (252.0)	Grey	Nonluminous	105	6	1890
17	WF	Low (42.0)	Grey	Nonluminous	105	6	1890
18	WF	Low (28.4)	Grey	Luminous	86	7	1806
19	WF	Low (28.4)	Grey/White Border	Luminous	86	7	1806
20	A	High (232.0)	Grey	Nonluminous	105	7	2205
21	A	Low (42.0)	Grey	Nonluminous	105	7	2205
22	A	Low (20.3)	Grey	Luminous	61	7	1281
23	A	Low (20.3)	Grey/White Border	Luminous	61	7	1281
Total number					2254		43,332
No. of Observers attended in the experiment						10	

Summary of Models' Performance Using Mean CV Values

Lightness

Experimental Type	I	II	III	Overall Ranking
No. of Phases	3	3	5	
CMC	66	30	39	5
CIE 1976	41	13	18	2
Nayatani	45	15	20	3
Hunt	47	16	24	4
ACAM	19	11	11	1

Colourfulness and Hue

Experimental Type	I	II	III	Overall Ranking
No. of Phases	3	3	5	
(Colourfulness)				
CMC	22	22	20	1
CIELAB	28	25	22	5
CIELUV	30	27	24	6
Nayatani	28	21	23	4
Hunt	20	24	20	1
ACAM	22	25	20	3
(Hue)				
Nayatani	10	15	14	2
Hunt or ACAM	8	6	6	1

Type I results: the mean CV values calculated from white surround phases

Type II results: the mean CV values calculated from black surround phases

Type III results: the mean CV values calculated from all grey surround phases.

Table 2

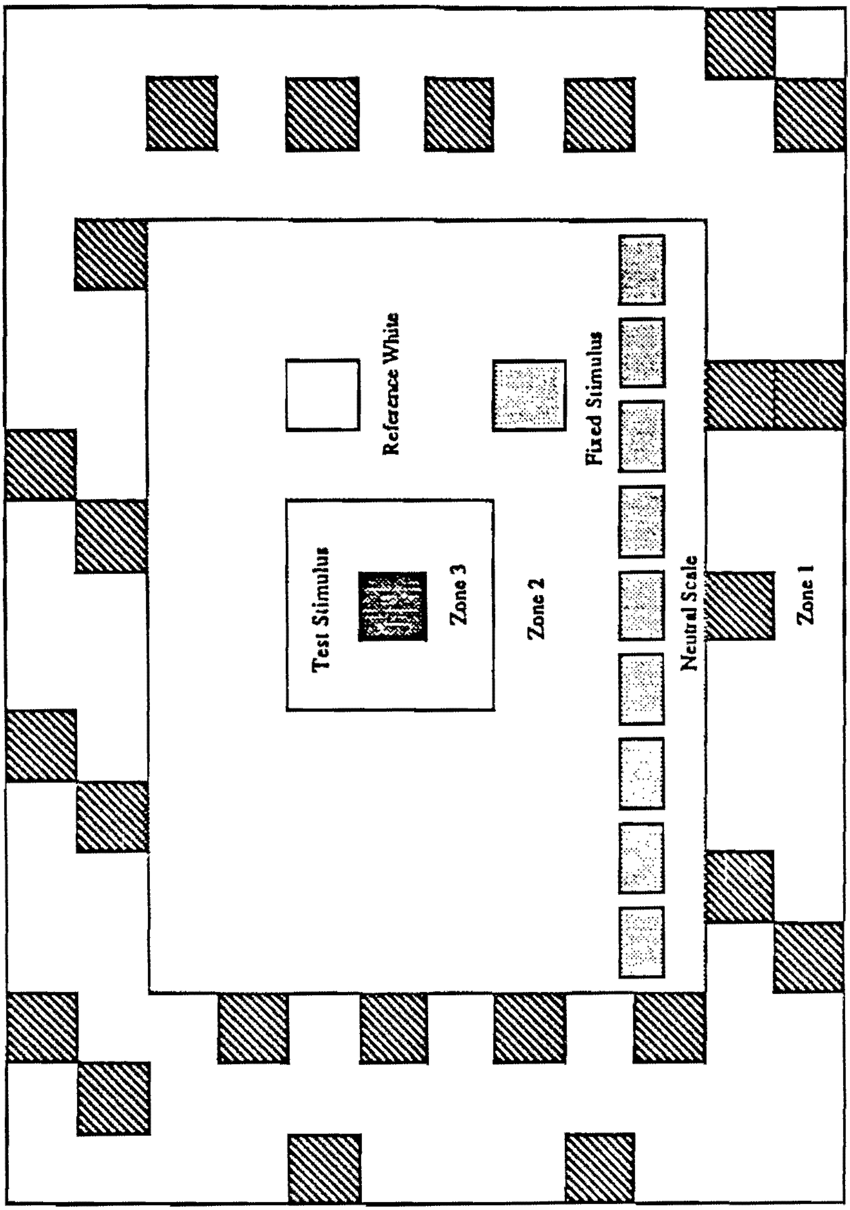

Figure 1 - Complex viewing field used for experiment

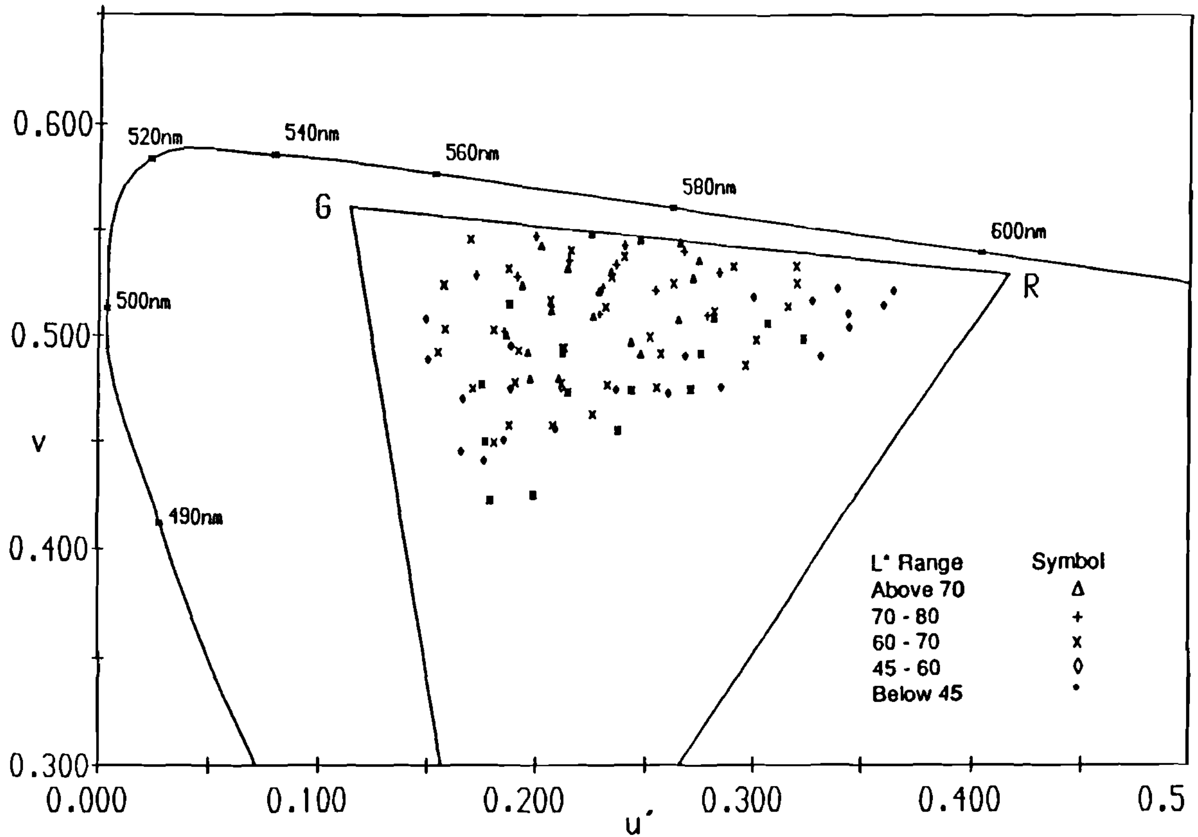

Figure 2 - Chromaticity co-ordinates of test samples using D50 illuminant.

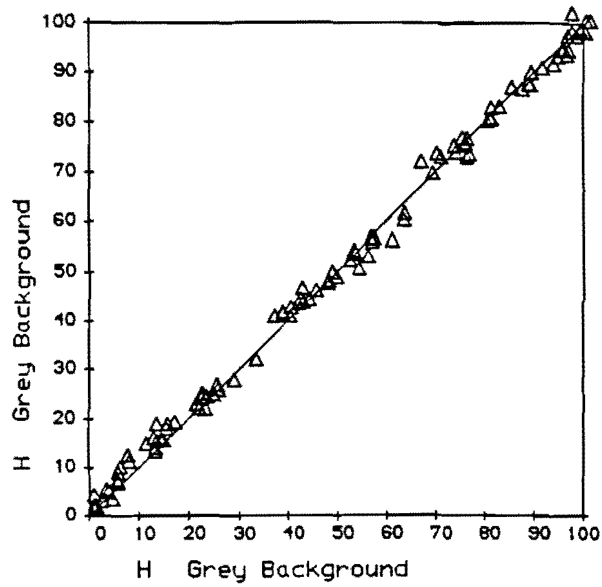

Figure 3(a) - Hue perception for high and low levels of illumination (non-luminous samples)

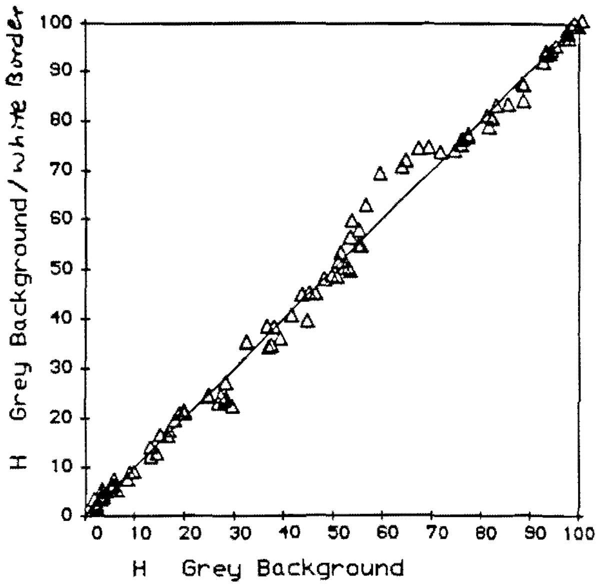

Figure 3(b) - Hue perception for luminous samples with and without white border

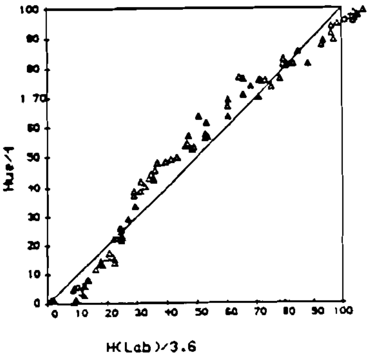

Figure 4(a) - CIE Lab

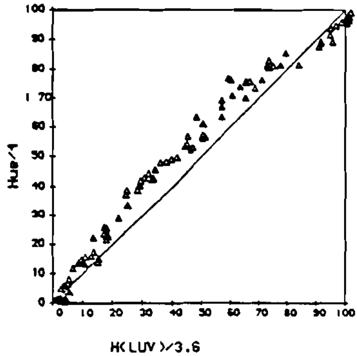

Figure 4(b) - CIELUV

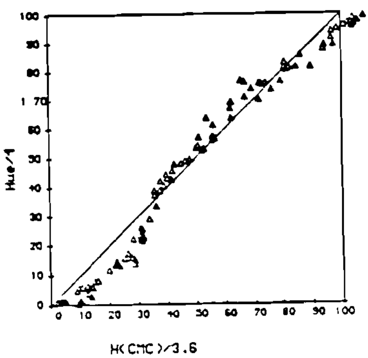

Figure 4(c) - CMC

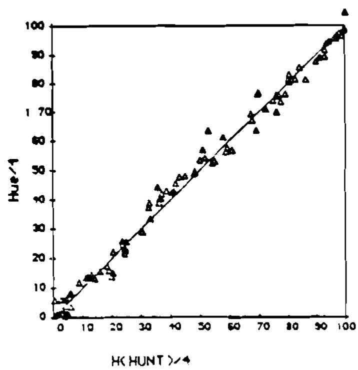

Figure 4(d) - Hunt

Figure 4 - Mean visual hue data as a function of CIELAB, CIELUV and CMC hue angle and Hunt hue.

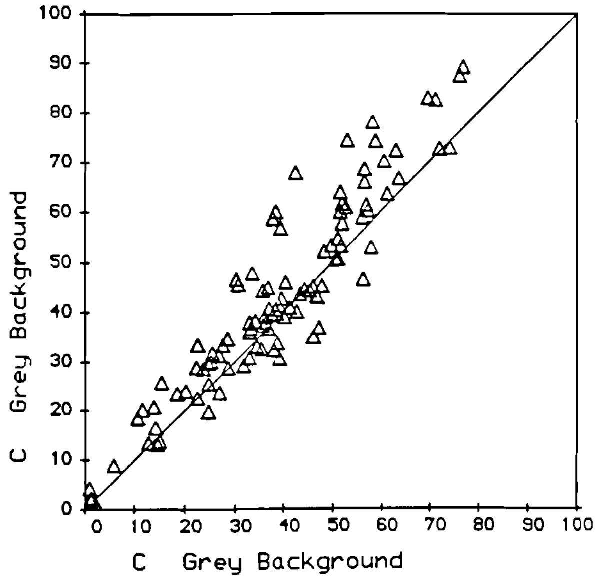

Figure 5(a) - Perceived colourfulness for high as a function of low illumination levels (non-luminous)

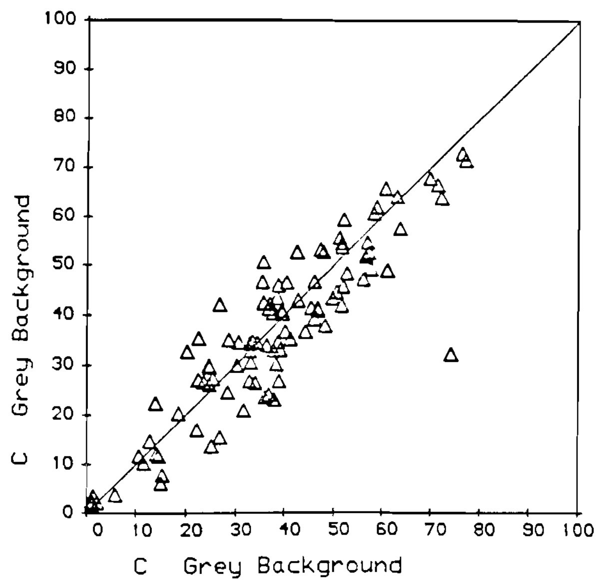

Figure 5(b) - Colourfulness for luminous as a function of non-luminous samples

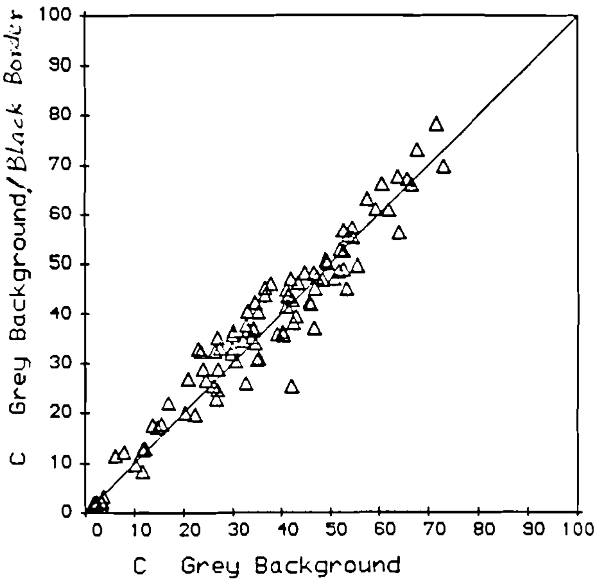

Figure 6(a) - Colourfulness of luminous samples with black border as a function of those with none.

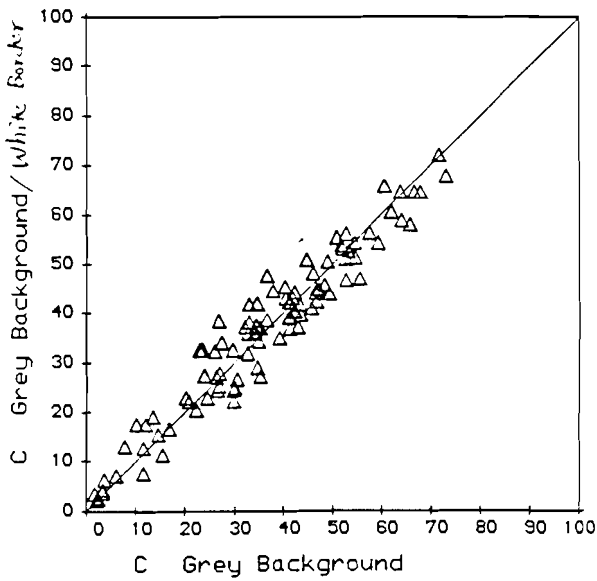

Figure 6(b) - Colourfulness of luminous samples with white border as a function of those with none.

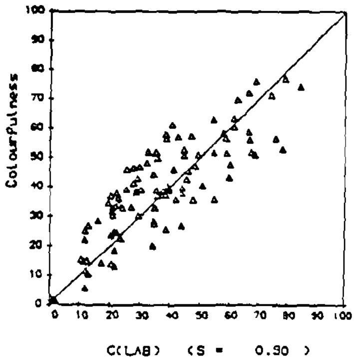

Figure 7(a) - CIELAB

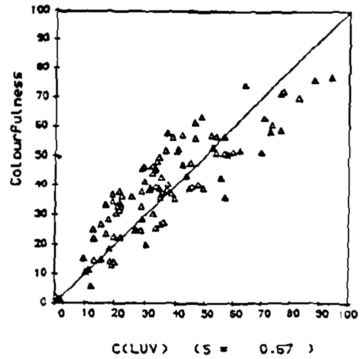

Figure 7(b) - CIELUV

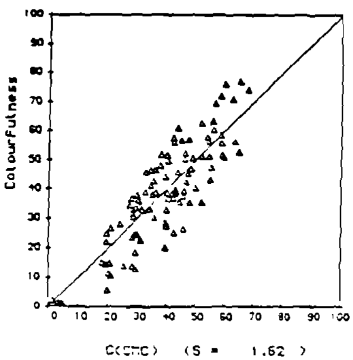

Figure 7(c) - CMC

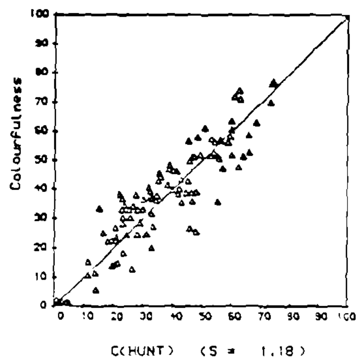

Figure 7(d) - Hunt

Figure 7 - Perceived colourfulness as a function of chroma for CIELab, CIELUV, CMC and Hunt colourfulness

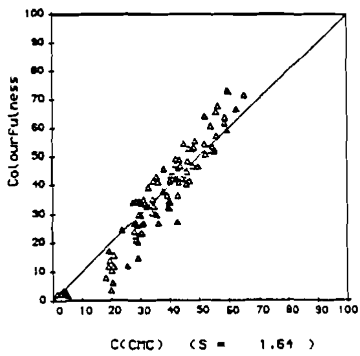

Figure 8(a) - CMC
(D50 illuminant)

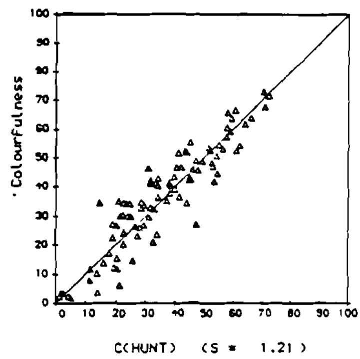

Figure 8(b) - Hunt
(D50 illuminant)

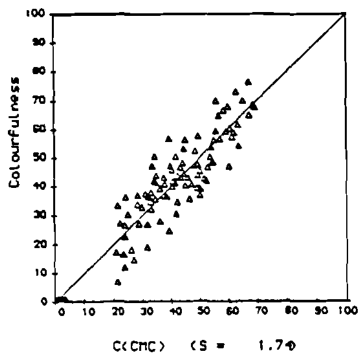

Figure 8(c) - CMC
(D65 illuminant)

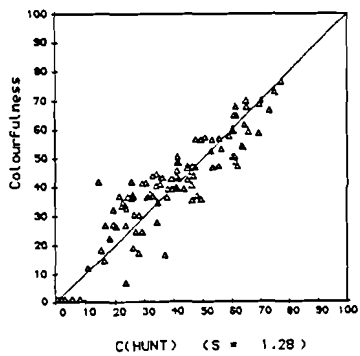

Figure 8(d) - Hunt
(D65 illuminant)

Figure 8 - Colourfulness as a function of CMC Chroma and Hunt colourfulness for D50 and D65 illuminants

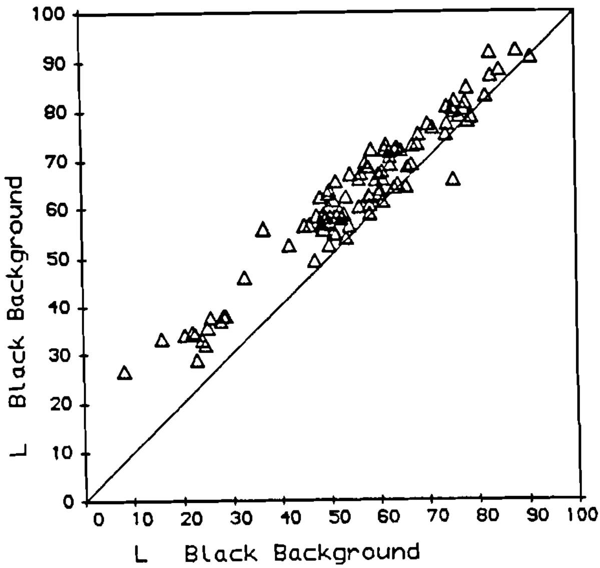

Figure 9(a) - Lightness of luminous as a function of non-luminous samples (black surround)

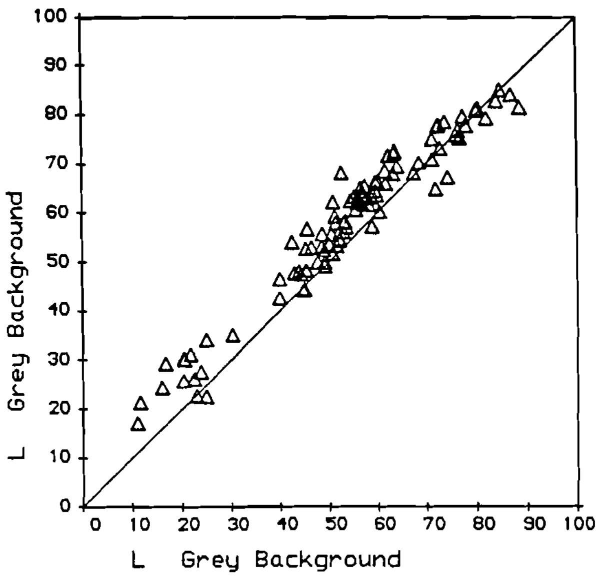

Figure 9(b) - Lightness of luminous as a function of non-luminous samples (grey surround)

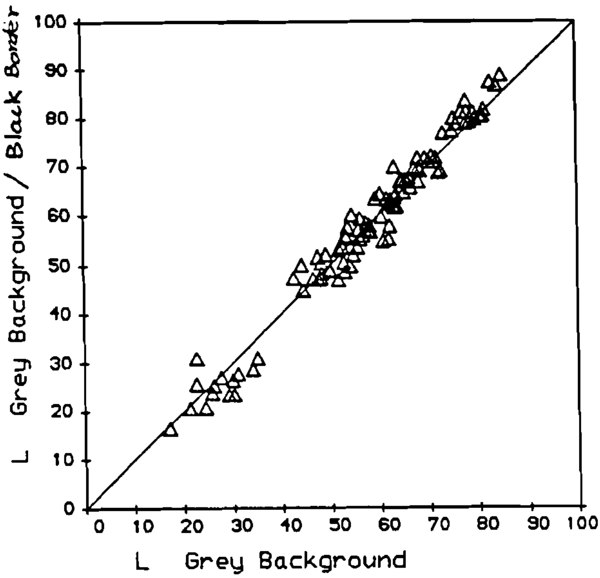

Figure 10(a) - Lightness of luminous samples with black border as a function of those without

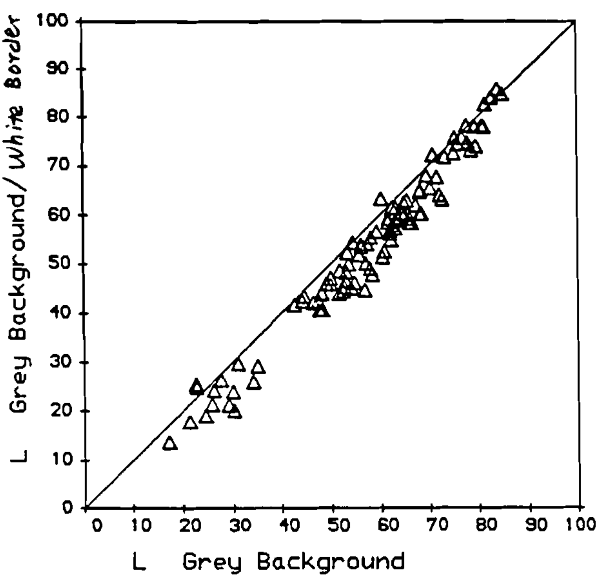

Figure 10(b) - Lightness of luminous samples with white border as a function of those without

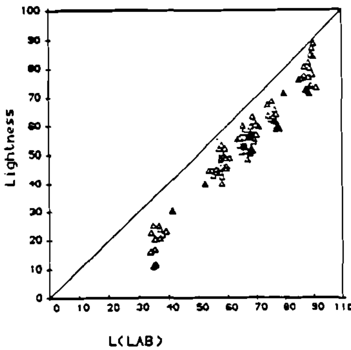

Figure 11(a) - CIELab/ CIELUV

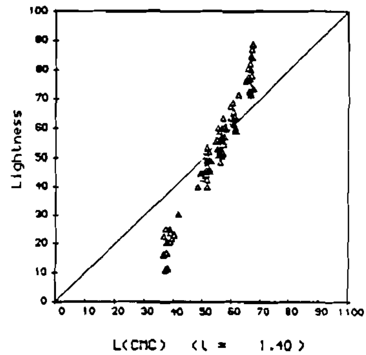

Figure 11(b) - CMC

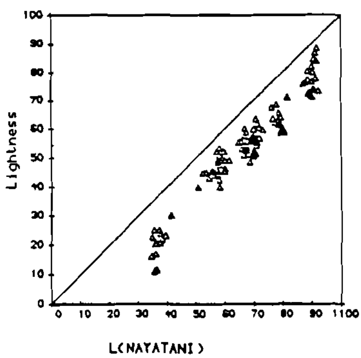

Figure 11(c) - Nayatani

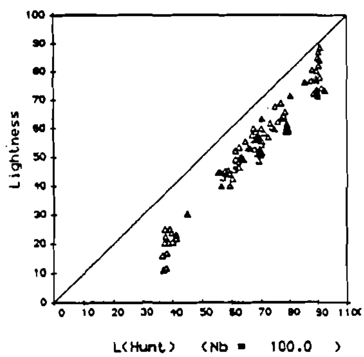

Figure 11(d) - Hunt

Figure 11 - Lightness as a function of CIELab, CMC, Nayatani and Hunt lightness predictions

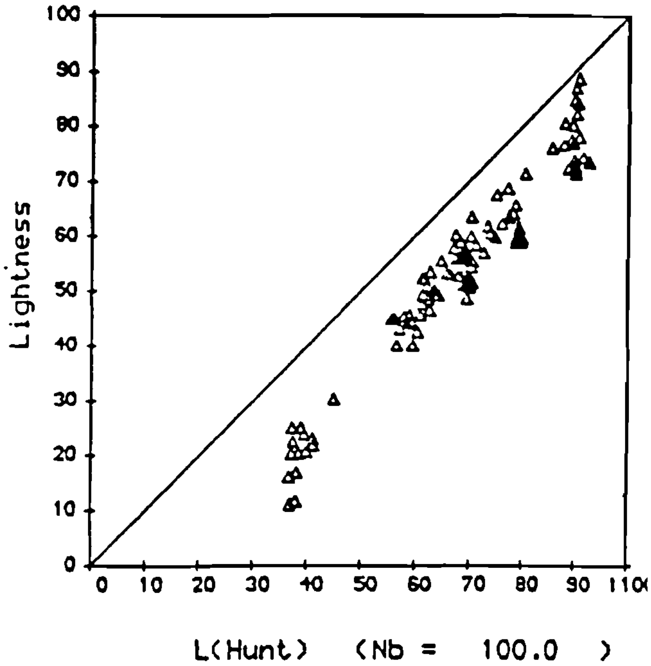

Figure 12(a) - Lightness as a function of Hunt model prediction with published constants

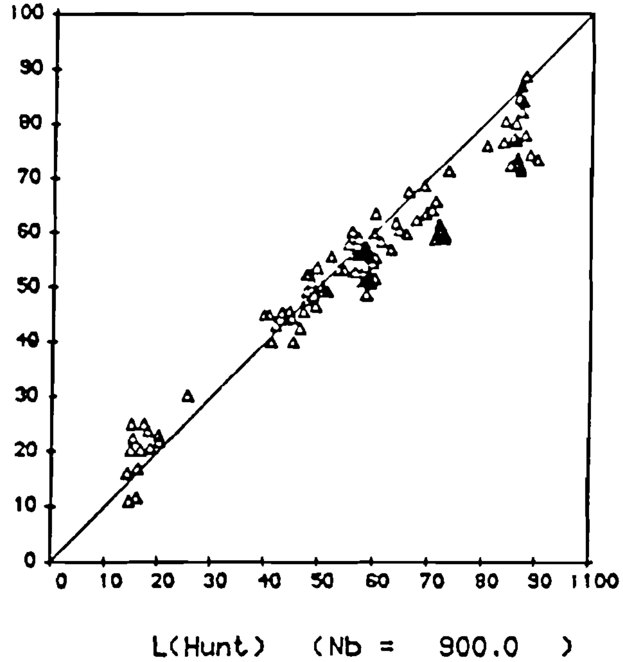

Figure 12(b) - Lightness as a function of Hunt model prediction with "best-fit" constants